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# *Strength Design Requirements of ACI-318M-02 Code, BS8110, and EuroCode2 for Structural Concrete: A Comparative Study*

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## Abstract

***This paper is intended to compare design requirements of the structural building codes from safety and economical point of view. Three different famous structural building codes have been adopted. These are the ACI 318M-02, BS8110:1985, and Euro Code2:1992. These codes have been compared in the strength design requirements of structural elements. The comparison include safety provisions, flexural design, shear design, and column design.***

***Throughout this study elaborated design models and criteria of the considered codes have been exhibited. Although the principles contained in these codes are basically the same, they differ in details. The comparison between results has shown that EC2 is more liberal in partial safety factors and strength design than ACI Code. After following this study, design engineers will discover easily that the transition among codes is not a difficult process.***

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## الخلاصــــة

*تقصد هذه الدراسة إلى أجراء مقارنة من الناحية الاقتصادية والأمان للمدونات الإنشائية للأبنية، من خلال تبني ثلاث مدونات مشهورة ومعتمدة عالمياً. المدونات هي: المواصفة الأمريكية للمتطلبات الإنشائية للخرسانة **ACI 318M-02** والمواصفة القياسية البريطانية **BS8110:1985** والمواصفة الأوربية **Euro Code2:1992**. تمت مقارنة هذه المدونات الثلاثة في إطار متطلبات القوة لكل مواصفة، وقد تضمنت مقارنة معاملات الأمان، وتصميم الانحناء للعتبات، وتصميم مقاومة القص، وتصميم الأعمدة.*

*في إطار المقارنة عرضت الدراسة النماذج والمعادلات التصميمية التي تطلبها كل مواصفة تفصيلياً. أفرزت الدراسة إن المواصفات الثلاثة تشترك في المبادئ الأساسية وتختلف في التفاصيل. كانت المواصفة الأوربية أكثر كرماً والأفضل من الناحية الاقتصادية.*

## 1. Introduction

This paper is devoted to focus a spot of light on strength design requirements for concrete structures. Three different commonly used structural building codes are adopted in this study. These are: the building code requirement for structural concrete ACI-318M-02 [1], the British standard for structural use of concrete BS8110:1985 [2]; and the Eurcode2 for the design of concrete structures [3].

The first set of building regulations for reinforced concrete was drafted under the supervision of Prof. Morsh of the University of Stuttgart and was issued in Prussia in 1904. Other countries followed soon after, and today most countries have their own building regulations. The aim of these regulations is to protect the public health and safety.

In the United States the design building code for concrete structures is the ACI 318M-02. This code witnesses major revisions every 6 years. BS8110 has been prepared under the direction of British Standard Institution in 1985. It supersedes CP110:1972, which was withdrawn. The search for harmonization of Technical Standards across the European Community has led to the development of a series of structural Euro Codes which are the technical documents intended for adoption throughout all the member states. Euro Code2 (EC2) deals with the design of concrete structures. Limit state principles (Ultimate Design Method) established by ACI and BS is also adopted by EC2.

Most Iraqi civil engineers are familiar with ACI code; however it is necessary to inform them about the other current British and European codes.

Before Euro Code2 and BS8110 are involved strongly in our design life, most engineers will need to be assured that they can be adopted as a practical design tool. Knowledge must be extended to cover the whole aspects of each part, as well as, the economical and the conservative results.

This study will attempt to summarize the principle design procedures required by ACI code, compared with their counterparts of BS8110, and EC2.

The three codes are compared in the context of design of primary structural elements and the information is given broadly about the essential features of their design criteria.

## 2. Safety Provisions

### 2-1 Loading

The three codes impose partial factors of safety for loads due to design assumptions and inaccuracy of calculation, possible unusual load increases, and constructional inaccuracies [4].

***Design load=characteristic load* partial load factor of safety ($\gamma_f$ ).***

The value of this factor $\gamma_f$ takes into account the importance of the limit state under consideration and reflects to some extent the accuracy with which different types of loading can be predicted, and the probability of particular load combinations occurring. **Table (1)** illustrates the values of partial factors of safety for the loadings, and a basic load combination stipulated by the three codes [1, 2, 3].

### Table (1) Basic Load Combinations and Partial Safety Factors ($\gamma_f$) at the Ultimate Limit State

| Code | Load (DL) | Load (LL) |
|---|---|---|
| **ACI318M-02** | 1.2 | 1.6 |
| **ACI318M-02 *(Alternative load factors)*** | 1.4 | 1.7 |
| **BS8110-1985** | 1.4 | 1.6 |
| **EC2-1992** | 1.35 | 1.5 |

Both ($\gamma_{dead}$) and ($\gamma_{live}$) are marginally in descending manner from ACI-318M reaching to the lowest values in EC2. For a typical member with DL=2LL, maximum uniformly distributed design load in EC2 would be 7.1% lower than that of the ACI Code, and 4.8% lower than that of BS8110.

## 2-2 Materials

As in BS8110, EC2 uses a basic material partial factor of safety ($\gamma_m$) [5]:

$$Design\ strength = \frac{characteristic\ strength}{material\ partial\ \ factor\ of\ \ safety\,(\gamma_m)}$$

The strength of the material will differ from that measured in a carefully prepared test specimen and it is particularly true for concrete where placing, compaction and curing are so important to the strength. Steel, on the other hand, is relatively consistent requiring a small partial factor of safety. Recommended values for $\gamma_m$ are given in **Table (2)**.

### Table (2) Material Partial Factors of Safety ($\gamma_m$) at the Ultimate Limit State

| Code | Concrete in Flexure or Axial Load | Concrete in Shear | Concrete in Bond | Reinforcement Steel |
|---|---|---|---|---|
| **BS8110-1985** | 1.5 | 1.25 | 1.4 | 1.15 |
| **EC2-1992** | 1.5 | 1.5 | 1.5 | 1.15 |

However, in ACI Code, the strength reduction factor Φ replaced the material partial safety factors of other codes. Φ in the ACI code is given different values depending on the state of knowledge, i.e., the accuracy with which various strengths can be calculated. Thus, the value for bending is higher than that for shear or bearing. Also, the Φ values simulate the

($\gamma_m$) values from the side that both reflect the probable quality control achievable, and reliability of workmanship and inspection [6].

In ACI code the factors Φ for under strength, called strength reduction factors, are prescribed as follows [1]:

| | *Φ Factors* | *Φ Alternative Factors* |
|---|---|---|
| *Flexure* | *0.90* | *0.90* |
| *Axial tension* | *0.90* | *0.90* |
| *Shear and torsion* | *0.75* | *0.85* |
| *Compression members spirally reinforced* | *0.70* | *0.75** |
| *Compression members tied reinforced* | *0.65* | *0.70** |
| *Bearing* | *0.65* | *0.70* |

## 3. Design of Section under Flexure

### 3-1 Design Criteria

Beams may fail by moment because of weakness in the tension steel or weakness in the compression concrete. Most beams are weaker in their reinforcing steel than in their compression concrete. Both codes and economy require such design. If the concrete reaches its full compressive stress just as the steel reach its yield-point stress, the beam is said to be a balanced beam at failure. Such a beam which requires very heavy steel, is rarely economical, and is not allowed by all codes. The balanced beam in ultimate strength design is fundamental to the philosophy of all the considered three codes.

The Codes limit the tensile reinforcement to a maximum value must be less than the balanced reinforcement area. ACI code limits the tensile reinforcement to a maximum of $0.75\rho_b$, while BS8110 and EC2 limit it to $0.76\rho_b{}^*$ and $0.53\rho_b{}^*$ respectively [1, 2, 3].

### 3-2 Stress Block

For design purposes real final stress distribution may be replaced adequately by an equivalent rectangle of compression stress (pioneered in USA by Whitney) [8].

For rectangular beam section, the shaded area of the rectangular stress block of **Fig.(1)** should be equal that of the real stress block and their centroids should be at the same level.

**Figure (1)** illustrates the stress block adopted by ACI code and compared to those used by BS8110 and EC2.

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* For combined compression and flexure, both axial load and bending moment are subjected to the same $\phi$ factor, which may be variable and increased to 0.9 as the axial compression decreases to zero.

* $\rho_{max}$ in BS8110 and EC2 is given in term of maximum neutral axis depth Xmax permissible before compression steel is to be provided. And the given values for $f_c'=30\ MP_a$ and $f_y=420\ MP_a$

**Table (3)** shows results of neutral axis depth against various reinforcing steel ratios for the adopted specifications. ACI model gives the advantages in terms of reinforcement area because of the resulting increase in the lever arm comparatively with BS8110 and EC2.

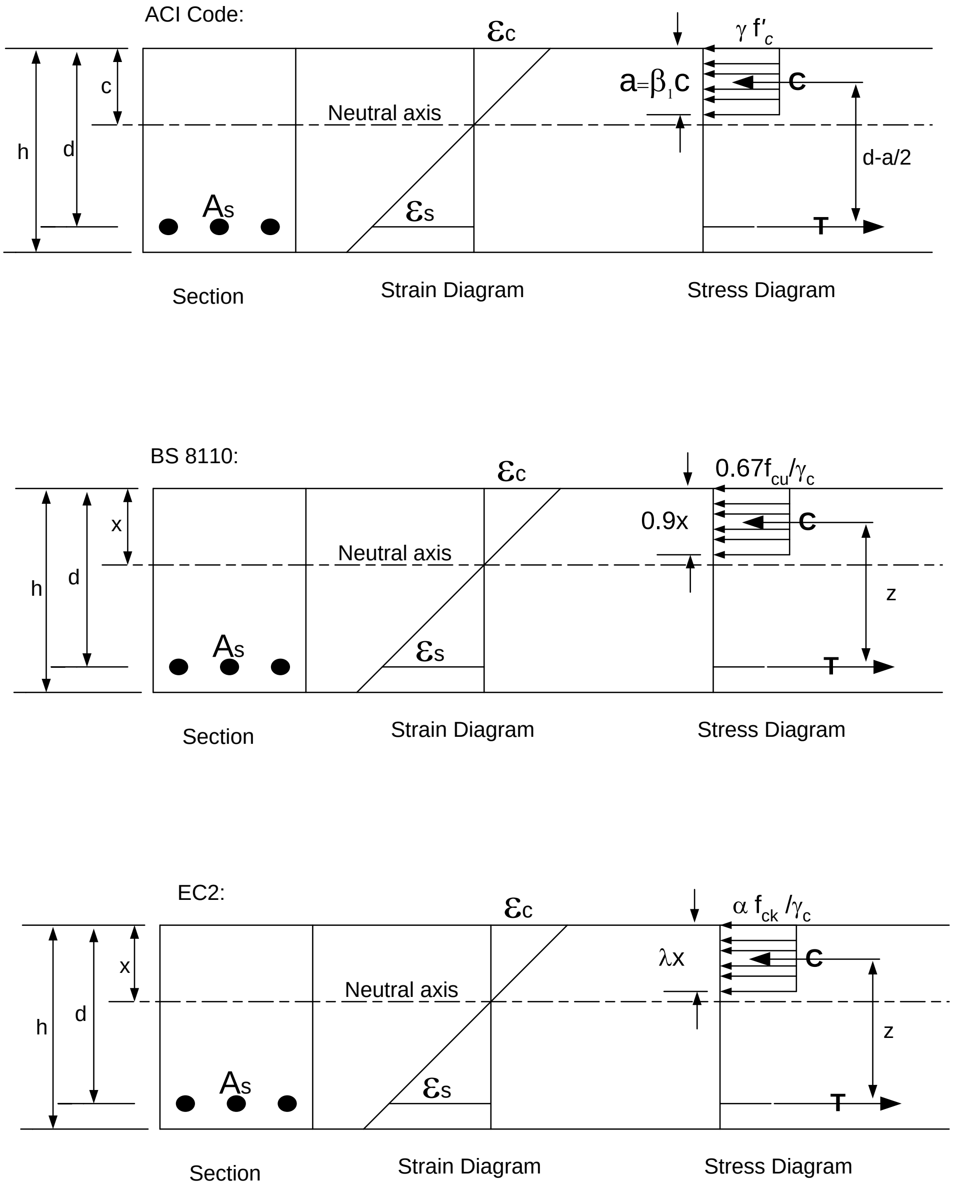

**Figure (1) Strain Distribution and Stress Block**

**Table (3) Neutral Axis Depth against Different Steel Ratios (Rectangular Section b*h, fc'=30 MPa, fy=420 MPa)**

| $\rho$ | 0.005 | 0.01 | 0.015 | 0.02 | 0.025 | 0.03 |
|---|---|---|---|---|---|---|
| **ACI Code** | 0.082d | 0.165d | 0.247d | 0.329d | 0.412d | 0.494d |
| **BS8110** | 0.122d | 0.243d | 0.365d | 0.487d | 0.609d | 0.730d |
| **EC2** | 0.134d | 0.269d | 0.403d | 0.537d | 0.671d | 0.806d |

### 3-2-1 Concrete Grades

ACI Code and EC2 allow the benefits of deriving a formula by using high strength concretes, while BS does not. The value of $f_{cu}$ should not be taken greater than (40 MPa) as stipulated by BS8110. Concrete strengths are referred in EC2 and ACI by cylinder strengths, which are (10-20%) less than the corresponding cube strengths used in BS8110**.

## 3-3 Design Formula

A rectangular section was analyzed under bending moment to avoid the necessity of using the ultimate concrete strain. Application of the unique two equilibrium equations at the section produces the design moment capacity criteria. Eq. (1), Eq. (2), and Eq.(3) represent design moment capacity formula producing by ACI Code, BS8110 and EC2 model respectively **[1,2, 3]**:

$$M = \phi \rho b d^2 f_y (1 - \frac{\rho f_y}{1.7 f'_c}) \quad \text{ACI} \quad \ldots\ldots\ldots \textbf{(1)}$$

$$M = \rho b d^2 \frac{f_y}{\gamma_m} (1 - \rho \frac{f_y \gamma_m}{1.33 f_{cu}}) \quad \text{BS} \quad \ldots\ldots\ldots \textbf{(2)}$$

$$M = \rho b d^2 \frac{f_y}{\gamma_m} (1 - \rho \frac{f_y \gamma_m}{1.7 f_{ck}}) \quad \text{EC2} \quad \ldots\ldots\ldots \textbf{(3)}$$

The only under reinforced beams are permitted by the considered three specifications. The resulting stretching of the steel will raise the neutral axis until the final secondary compression failure occurs at the compression strain which has been taken in ACI Code as $\varepsilon_c$=0.003, and $\varepsilon_c$=0.0035 in BS8110, and EC2.

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** The coefficient R is used to convert cylinder strength to cube, where R=0.76+0.2log($f'_c$/20)

## 3-4 Effect of ρ on Moment Capacity

To trace the ultimate moment capacity produced from equations 1,2, and 3, a rectangular section with $f_c^{'}=30\ MP_a$ and $f_y=420\ MP_a$ has been analyzed. **Figure (2)** shows the results of analysis. It was found that the results showed similar behavior for BS8110 and EC2 due to the similarity of modeling and convergence of safety factors. On the other hand, the matter was different in ACI formula. ACI formula gives higher moment capacity for lower steel ratios, while this virtue becomes of secondary effect comparatively with BS and EC when the steel ratio increase over $\rho_{max}$ in doubly reinforced sections because of the effect of compression steel ratio which has contribute highly in increasing moment capacity.

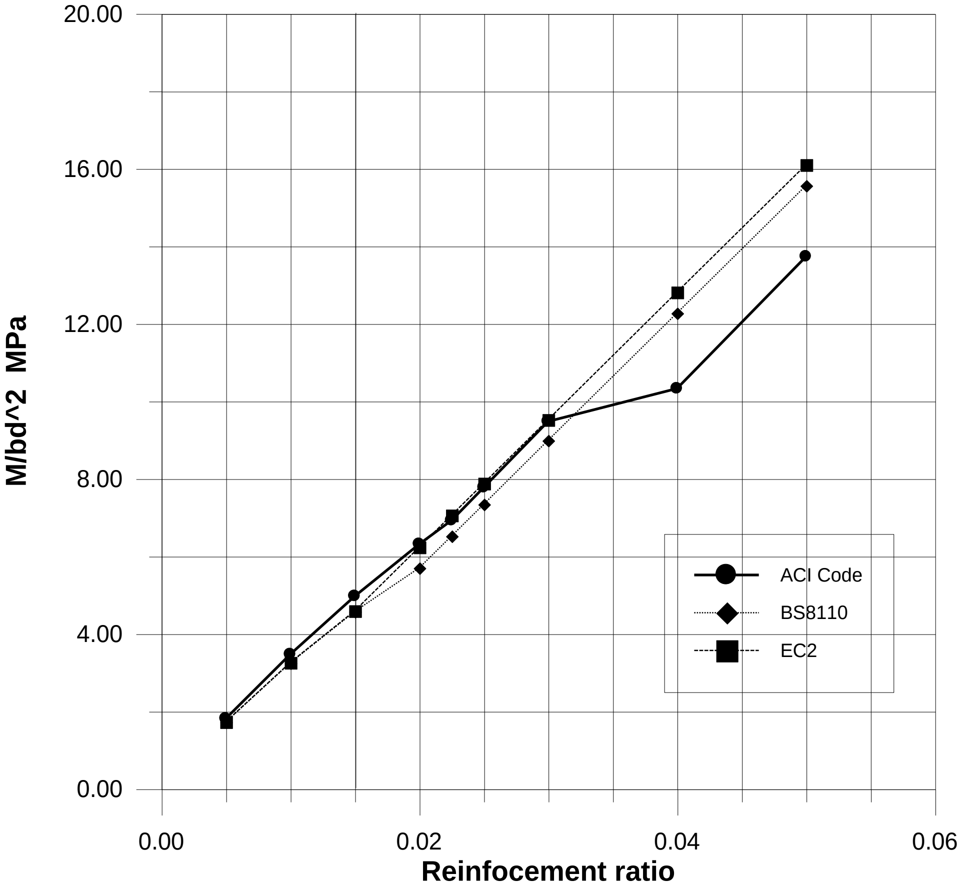

**Figure (2) Effect of ρ on Ultimate Moment Capacity**
**(*fc'=30 MPa and fy=420 MPa*)**

# 4. Design of Shear

## 4-1 Concrete Shear Strength

The shear in a reinforced concrete beam without reinforcement is carried by a combination of three main components. These are concrete in compression zone, dowelling action of tensile reinforcement, and aggregate interlock across flexural crack. The actual behavior is complex, and difficult to analyze theoretically but by applying the results of many experimental investigations, reasonable simplified procedures for estimating concrete shear strength can be developed.

In EC2 as in the other two codes, the concrete shear strength depends on concrete compressive strength, effective beam depth, width and tension steel ratio. The recommended design shear strength of the concrete alone for comparison among the adopted three codes is as given in the following equations:

**EC2 [3]:**

$$V_{Rd1} = 0.035 f_{ck}^{2/3} k(1.2 + 40\rho) b_w d \quad \text{EC2} \;\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textbf{(4)}$$

where:

*k= (1.6-d) >1 or 1 where more than 50% of tension reinforcement is cut, d in meter,* $\rho < 0.02$

**BS8110 [2,4]:**

$$V_c = \frac{0.79}{\gamma_c}\left(100\rho\frac{f_{cu}}{25}\right)^{1/3}\left(\frac{400}{d}\right)^{1/4} b_w d \quad \text{BS8110} \;\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textbf{(5)}$$

where:

$$\rho = \frac{A_s}{b_w d} \le 0.03$$

$$\left(\frac{400}{d}\right) \ge 1$$

$$f_{cu} \le 40\ \text{MPa}$$

While **ACI Code** [1] suggests two equations to estimate concrete shear strength:

$$V_c = \frac{\sqrt{f'_c}}{6} b_w d \quad \text{ACI Code} \;\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textbf{(6)}$$

or

$$V_c = \left[\frac{\sqrt{f'_c}}{7} + \frac{120}{7}\rho_w \frac{V_u d}{M_u}\right] b_w d \qquad \text{ACI Code} \quad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textbf{(7)}$$

$$V_c \le 0.3\sqrt{f'_c}\, b_w d \qquad \text{ACI Code}$$

where:

$$\text{depth/shear span ratio} = \left|\frac{V_u d}{M_u}\right| \le 1.0$$

The engineer may use either Eq. (6) or Eq. (7) and will soon note that only a few situations give large differences between them [8].

From the above concrete shear strength, it may be seen that the shear stress of concrete increases for shallower sections and for section with larger percentage of tensile reinforcement. The longitudinal tension bars contribute to shear resistance by their dowelling action and they help to prevent shear cracks from commencing at small tension cracks, also they increase the depth of compression concrete zone [4, 8].

It is obvious that concrete shear strength Equations (4), (5), (6), or (7) is related empirically to the concrete compressive strength. The principal stresses at diagonal shear cracks are inclined. If the diagonal tension exceeds the limit tensile strength of concrete, then concrete, is not adequate alone to carry the applied shear force. Concrete tensile strength has determined empirically by correlation between various measures of tensile strength and square or third root of the compressive strength [9].

**Figure (3)** shows the increasing in the allowable shear stress of concrete as the concrete compressive strength increases. For normal strength concrete, BS8110 shear strength formula Eq. (5) gives 20-55% over the strength calculated by EC2 Eq.4, while it is of 20-30% over values of ACI Code Eq. (7).

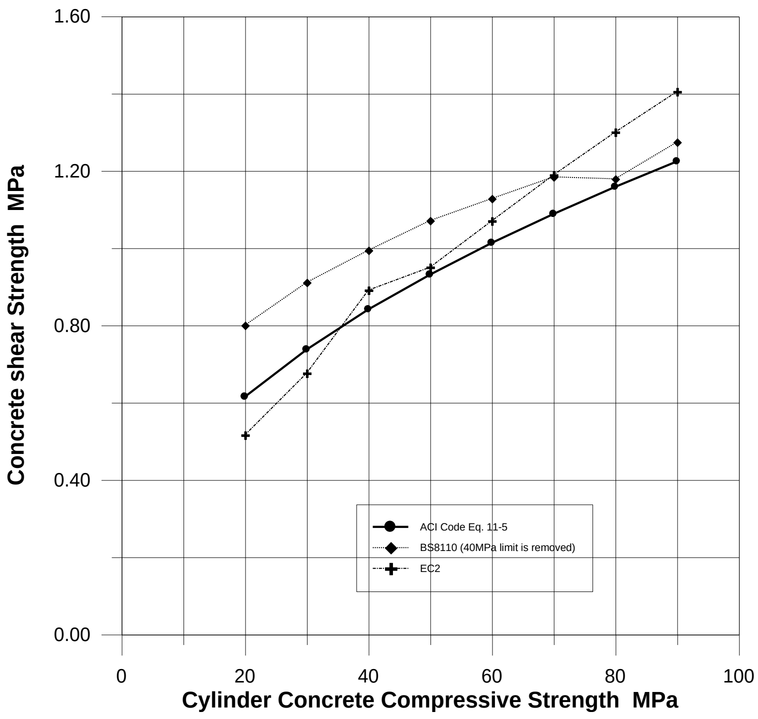

**Figure (3) Effect of Concrete Compressive Strength on Allowable Concrete Shear Strength ($\rho$=0.02)**

## 4-2 Minimum Shear Reinforcement

When checking a normal shear, EC2 is the same as ACI Code and BS8110 in that nominal shear stresses below which only minimum shear reinforcement to be provided. The minimum shear reinforcement requested by the codes is as summarized in the following equations:

$$A_v = \frac{0.48 b_w S}{0.87 f_y} \quad \text{EC2} \quad \dots\dots \quad \textbf{(8)}$$

where:

$f_{ck} = (25-30)\,\text{MPa}$

$S \le 0.65d, 300\,\text{mm}$

$$A_v = \frac{0.4 b_w S}{0.87 f_y} \quad \text{BS8110} \quad \dots\dots \quad \textbf{(9)}$$

where:

$f_{cu} = 40\,\text{MPa}$

$A_v = \frac{\sqrt{f'c}\, b_w S}{16 f_y}$

but not less than:

$$A_v = \frac{0.33 b_w S}{f_y} \quad \text{ACI Cod} \quad \dots\dots \quad \textbf{(10)}$$

where:

$S \le 0.5d,\ 600\,\text{mm}$

The EC2 limitation given by Eq. (8) is more conservative than those given by Eqs. (9) and (10) of BS8110 and ACI Code respectively.

## 4-3 Maximum Applied Shear Force

Large shearing forces are liable to cause crushing of the concrete along the direction of the principal compression stresses. EC2 and BS8110 limit the maximum applied shear stress at section close to support to certain values calculated by using the following Eq. (11) and Eq. (12) respectively [3,5]:

$$V \le 0.3 \nu f_{ck} \quad \text{EC 2} \quad \dots\dots \quad \textbf{(11)}$$

where:

$\nu = 0.7 - \frac{f_{ck}}{200} \ge 0.5$

$$V \leq 0.8\sqrt{f_{cu}} \quad \text{or} \quad 5\,\text{MPa} \quad \text{BS8110} \quad \text{(12)}$$

While the ACI Code limits the maximum applied shear stress at section in another way. It has limited the shear strength provided by shear reinforcement in order to ensure that the amount of shear reinforcement is not too high [1, 4]:

$$V_s \leq \frac{2}{3}\sqrt{f'_c}\; b_w d \quad \text{ACI Code} \quad \text{(13)}$$

This means that the maximum allowed shear stress at a section may be written in this formula:

$$V \leq 0.83\sqrt{f'_c} \quad \text{ACI Code} \quad \text{(14)}$$

The values produced from the three different codes formulae are so close, i.e. for a section with f'c=30 MPa, the maximum limiting allowed shear strength should be less than:

***4.95 MPa according to EC2 formulae***
***4.90 MPa according to BS8110 formulae***
***4.56 MPa according to ACI Code formulae***

## 5. Design of Element under Bending Plus Axial Compression

### 5-1 Basic Equations

As in ACI Code, BS8110 and EC2 do not give separate guidance on the approach to be used in designing a column under a moment and axial force. For practical purposes as with ACI the rectangular stress block that used for the design of beams may also be used for the design of columns. **Figure (4)** represents the cross-section of a member with typical strain and stress distribution for varying positions of neutral axis.

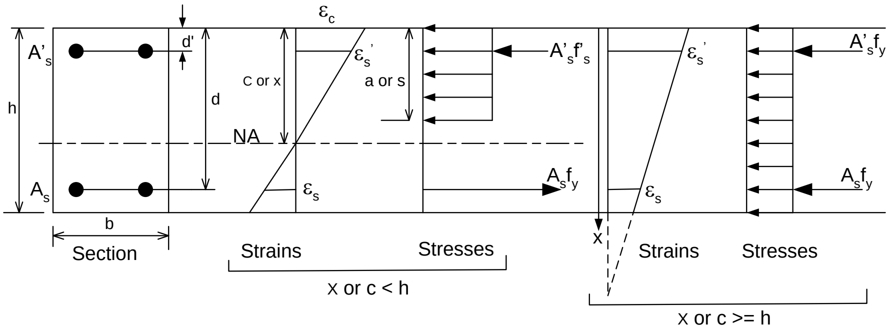

**Figure (4) Bending Plus Axial Compression with Varying Position of the Neutral Axis**

## 5-2 Modes of Failure

The relative magnitude of the moment (M) and the axial compression force (P) govern whether the section will fail in tension or in compression. M-P interaction diagrams can be constructed for any shape of cross-section by applying the basic equilibrium equations and strain compatibility.

Three types of failure will appear on the interaction diagram. With large effective eccentricity (e=M/P) a tensile failure is likely, but with a small eccentricity a compression failure is more likely. M-P interaction charts for a (500*300) mm section with design data shown in **Fig.(5)** have been plotted taking stress distribution blocks adopted by the three codes **Fig.(2)**.

A further limitation on column strength is imposed by ACI Code as well as the two others, in order to allow for accidental eccentricities of loading.

This would be included by imposing an upper limit of pure axial column capacity less than the calculated ultimate strength. This upper limit is taken as 0.80 times the calculated strength of tied column as stated by ACI Code and 0.87 as requested by BS8110. This reduction in ultimate strength belongs to that all considered codes ordered that each column should not be designed for a moment less than ($P_o * e_{min}$), where $e_{min}$ is the minimum eccentricity of the axial load and has the following value for tied column:

$e_{min} = \min(0.05h, 20mm)$ ***............BS8110 & EC2***

While the ACI code requires something similar by setting an upper limit on the maximum axial load Pu, as shown by the horizontal line in **Fig.(5)**.

The parameter h represents the overall size of the column-cross section in the plane of bending.

The interaction diagrams for factored design column strength under a provision of each code have been calculated and plotted, as shown in **Fig.(5)**. The horizontal line appears within each chart belonging to the reduction of pure axial compression force due to the minimum imposed eccentricity [4]. The charts of the factored design strength for the adopted example give close agreement between EC2 and BS8110 because the similarity in strain distribution diagrams and stress blocks, on the other hand, the closeness in material partial safety factors. While the chart of ACI Code moves away from others. ACI Code design criteria seem obviously less economical and widely conservative.

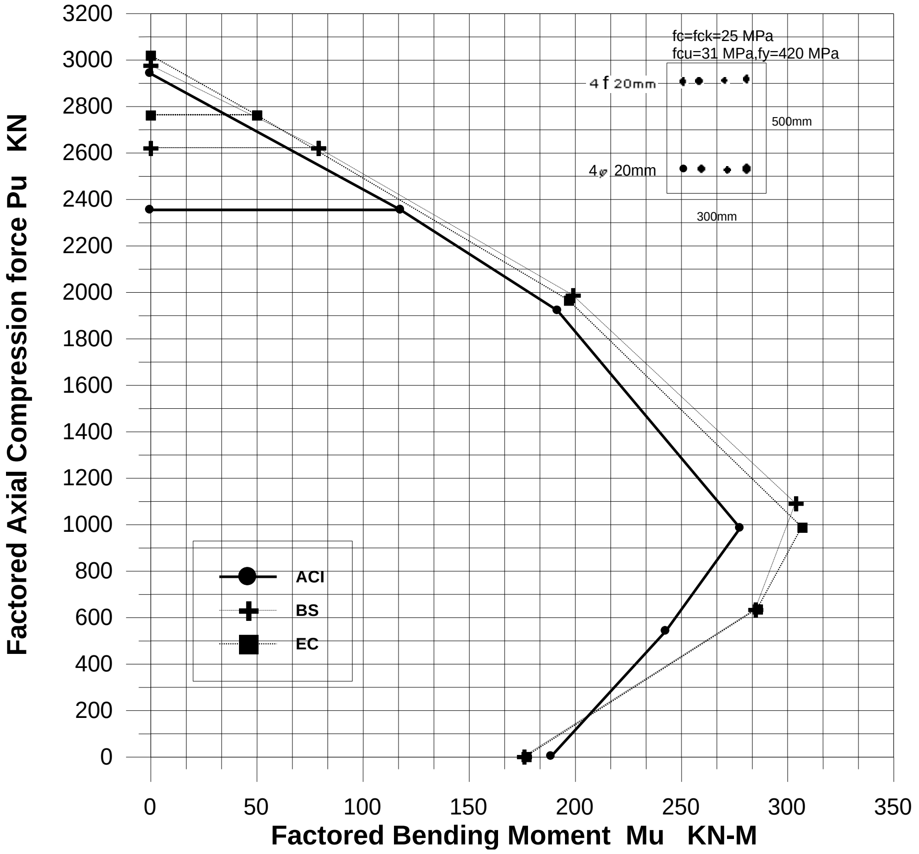

**Figure (5) Interaction Diagrams for Ultimate Factored Design Strengths in Combined Bending and Axial Compression Load**

## 5-3 Columns Longitudinal Reinforcement

The minimum or maximum amount of longitudinal reinforcement should not violate the limits stipulated by codes. **Table (4)**; gives minimum and maximum steel ratio requested by ACI code, BS 8110, and EC2 **[1, 2,3]**.

**Table (4) Minimum and Maximum Column Longitudinal Steel Ratio**

| Code | Min. Steel Ratio | Max. Steel Ratio |
|---|---|---|
| **ACI 318M-02** | 0.01 | 0.08 |
| **BS8110** | 0.004 | 0.06 |
| **EC2** | 0.003 | 0.08 |

Codes also require a minimum of four bars in a rectangular column (one bar in each corner) and six bars in a circular column.

## 6. Conclusions

The main conclusions from this study can be summarized as follow:

1. Although the principles contained in the considered building regulations are generally the same, they differ in details.
2. In general EC2 and BS8110 are not very different from ACI Code in terms of the design approach. They give similar answers and offer scope for more economical concrete structures.
3. A true factor of safety can only be determined by comparing design loading with that at collapse. While partial safety factors for materials and loadings are not safety factors; they only reflect degrees of confidence in material properties and accuracy of load prediction.
4. EC2 and ACI Code are more extensive for design requirements point of view than BS8110. For example in permitting using higher concrete strength.
5. After study some numerical examples; EC2 and BS8110 show close agreement in flexure plus axial compression results, while ACI Code results diverge in a less economical side.
7. BS8110 exhibits larger allowable design shear strength of concrete.
8. ACI Code, EC2, and BS8110 give a very close design moment capacity for steel ratios within or less than balanced steel ratio. But EC2 is more generous in doubly reinforced sections.

## 7. References

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## *Notations*

| | |
|---|---|
| A: | Depth of equivalent rectangular ACI Code stress block |
| $b_{w}$: | Web width |
| c or x: | Distance from extreme compression fiber to neutral axis |
| d: | Distance from extreme compression fiber to centroid of tension reinforcement |
| s: | Depth of equivalent rectangular EC2 and BS8110 stress block |
| $A_s$: | Area of tension reinforcement |
| $A_v$: | Area of shear reinforcement within a distance S |
| M: | EC2 and BS8110 moment at section |
| $M_u$: | Factored ACI Code moment at section |
| S: | Spacing of stirrups |
| V: | Nominal shear strength of section |
| $V_c$: | Nominal shear strength provided by concrete |
| $V_{Rd1}$: | EC2 concrete shear strength |
| $V_s$: | Nominal shear strength provided by shear reinforcement |
| $f_c'$: | Specified ACI Code cylinder compressive strength of concrete |
| $f_{ck}$: | Specified EC2 cylinder compressive strength of concrete |
| $f_{cu}$: | Characteristic BS8110 cube compressive strength of concrete |
| $f_y$: | Specified yield strength of reinforcement |
| $\alpha$: | EC2 parameter for the rectangular stress block, $\alpha$=0.85 |
| $\beta_1$: | Concrete ACI Code stress block depth factor |
| $\varepsilon_c$: | Ultimate strain of concrete |
| $\varepsilon_s$: | Tension steel strain |
| $\varepsilon_s'$: | Compression steel strain |
| $\phi$: | ACI Code strength reduction factor |
| $\gamma$: | ACI Code parameter for the rectangular stress block, $\gamma$=0.85 |
| $\gamma_f$: | Partial safety factor for load |
| $\gamma_m$: | EC2 and BS8110 partial safety factor for strength of materials |
| $\gamma_c$: | Partial safety factor for strength of concrete |
| $\gamma_s$: | Partial safety factor for strength of steel |
| $\lambda$: | Concrete EC2 stress block depth factor |
| $\rho$: | Steel ratio of longitudinal tension reinforcement |